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Published in:
Smart Energy

DOI (link to publication from Publisher):
10.1016/j.segy.2023.100111

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Smart Energy 11 (2023) 100111

Contents lists available at ScienceDirect

Smart Energy

journal homepage: www.journals.elsevier.com/smart-energy

The green transition of industry – An introduction to IndustryPLAN

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ARTICLE INFO

Keywords:
Energy efficiency
Industry
Energy system modelling
Smart energy systems
EnergyPLAN

ABSTRACT

The green transition of industry has an essential role in meeting the Paris Agreement targets. Transition strategies should integrate a balance between energy efficiency, electrification, and renewable energy. Focus should be on enabling industry to play an active role in the integration of variable renewable energy sources and the sector-coupling needed for the utilisation of excess heat. Industry in the European Commission's net-zero emission scenarios such as EU 1.5 TECH in "A Clean Planet for all" is based on a top-down methodology with the risks of overinvestments, blind investments, non-concrete general pan-industrial investments, and unrealistic implementation rates. This paper introduces seven guiding principles and a freeware tool, IndustryPLAN, to open the "black box" of industry, quantify such strategies and apply them to EU-27 + UK. The tool enables the user to conduct country-specific, sector-specific or aggregated European analyses of climate mitigation measures by implementing best available technologies, innovative measures and technologies, electrification, shift to hydrogen-based processes, and excess heat utilisation. Also, resilience against fluctuating fuel, electricity and technology prices can be analysed to illuminate geopolitical or supply chain issues. The combination of the guiding principles methodology and the IndustryPLAN tool identifies at least 30% short-term feasible final energy demand savings and possible full decarbonisation with a 100% renewable energy supply for industry.

1. Introduction

The industrial development in Europe has been the core foundation of the social and economic development in the EU. However, since World War II for many countries in Europe, this has meant a very large increase in the use of energy and particularly fossil fuels. Access to cheap coal was the foundation of the Coal and steel union – the predecessor of the current EU. In recent years, we have however seen stronger and stronger pressure to transition the entire energy system, including the industry sector, to renewable energy sources. For the EU, this is apparent in the vision put forward by the EU Commission – A Clean Planet for all scenarios [1], part of a long-term strategy for the EU to transition to a 100% climate-neutral society, and a commitment to the global objectives of the Paris agreement [2].

The holistic transition of the energy system is the focal point of the Smart Energy Systems approach, representing a paradigm shift away from single-sector thinking and instead emphasising the interrelation and interdependency of all energy sectors [3]. The main thesis of the Smart Energy Systems approach is that identifying least-cost solutions for renewable energy integration in 100% renewable energy systems requires merging electricity, heating, transport, and industry sectors, coupled with storage options across a wide range of temporal scales, to enable the required flexibility for integration of fluctuating renewable energy sources [4].

Industrial activity accounts for approximately one-third of the global energy demand, underlining the importance of establishing renewable energy alternatives in the industry sector as part of the broader energy system transition. In the EU27 countries, industrial energy demands account for 25.8% of the overall final energy demand [5] and 19.9% of greenhouse gas emissions (excluding indirect emissions related to electricity consumption) [6].

In "A Clean Planet for all"-scenarios, the depiction of industry is heavily influenced by the top-down methodology applied in which the future development is only connected to GDP expectations and assumed energy efficiency (EE) improvements. While scenarios in the report do make suggestions for changes in industry, these scenarios focus on EE

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https://doi.org/10.1016/j.segy.2023.100111
Received 8 February 2022; Received in revised form 13 June 2023; Accepted 23 June 2023
Available online 6 July 2023
2666-9552/

improvements without specifying what the concrete potential technological changes are, and without investigating the underlying industrial sectors and their processes. This top-down approach poses substantial risks.

- Overinvestments
- Blind investments
- Non-sector and process-specific general pan-industrial investments
- Unrealistic implementation rates

Accurately depicting the industry sector has however traditionally been challenging, and thus the sector has largely been de-emphasised, generalised, or aggregated in energy system models and energy strategies, resulting in the industrial sector largely being considered as a "black box" in energy system models and scenarios [7]. This may be for several reasons, including the lack of access to high-quality disaggregated industrial energy demand data, or because of the inherent difficulties of analysing the industrial sector due to its heterogeneity [8] as it is comprised of a multitude of technologies and processes.

It is pertinent that we learn more about the industry sector from a bottom-up perspective, enabling the disaggregation of the industry sector that is necessary to accurately reflect on the role and impact of the sector in future renewable energy systems [9]. Even if it is well established that end savings would benefit the transition of the industry sector and the energy system in general, it remains uncertain to what extent the needed technologies and processes are presently available, and "how much" end savings is technically and economically feasible. Similar uncertainties exist for other energy mitigation measures such as electrification, power-to-X (PtX), solid biomass fuel, or excess heat extraction through district heating (DH) systems. All these technologies and solutions are needed in the ensuing industry sector transition, however, prioritising them remains a challenge. Accurately determining what can be done given the technologies available today is a pivotal first step to understanding the interplay of EE and mitigation measures and the interaction of the industry sector from a holistic energy system perspective.

Many existing studies assess industry on a sub-sector level and provide detailed information on technologies and processes for energy savings and emission reduction potentials for that specific sector, e.g. the paper and pulp [10], chemical [11], or iron and steel sectors [12,13]. While such studies provide detailed knowledge of the sub-sector processes and relevant energy transition measures, they are generally detached from the remaining industry sectors, and equally important, from the rest of the energy system. However, to understand the potential industry sector contribution to the long-term renewable energy transition, we need more comprehensive modelling approaches for the entire industry sector and connect this to the surrounding energy system [14].

Energy system modelling is a well-established part of designing and comparing energy system scenarios and thereby determining the most feasible long-term energy transition pathways for the complete energy system. A variety of energy system modelling tools exist, with significant variations in key model characteristics, e.g. simulation/optimisation-based approaches, or bottom-up/top-down approaches [15]. Common to most of such holistic cross-sectorial energy system modelling tools is that the modelling of the industry sector has traditionally been relatively simple in tools such as UK MARKAL [16], ETSAP-TIAM [17] or EnergyPLAN [18].

The FORECAST model developed by Fleiter et al. [19] is an example of a bottom-up simulation model for modelling energy scenarios for the industrial, services and residential sectors, of which the industry sector module is most relevant to this study. The model covers the entire industry sector by including a broad range of sub-sector-specific industrial processes and potential mitigation measures, to aid strategic decision-making by establishing possible transition pathways. The model has mainly been applied in a German and European context, e.g. in a study on decarbonisation pathways for the German industry sector [20]. The online documentation for the model includes technologies and input parameters but the model itself is not publicly available, and the energy system perspective remains somewhat confined and less holistic than in traditional integrated energy system models like EnergyPLAN.

In a review of technologies and methods for the decarbonisation of industry sectors, Bataille et al. [21] present alternative decarbonized production methods for typical high-volume industrial products. Technologies for decarbonisation include electrification e.g., through electric arc furnaces in the iron and steel sector, chemical pulping for pulp and paper, and carbon capture use and storage (CCUS) for process emissions in cement production. Bataille et al. categorise a shift to solid biomass fuel as an immediate option, carbon capture and storage as a near-future option, and electrification (combined with hydrogen) as a long-term option, concluding that the many emerging technologies for decarbonising the energy-intensive industry, are generally poorly represented in existing modelling frameworks and policy discussion.

Investigating the potential for decarbonising energy-intensive industry processes through electrification, Lechtenböhmer et al. [22] analyse the implications of complete electrification of the most energy-intensive materials in industry. The authors find that while complete electrification is technically possible in the future, the associated increase in industrial electricity demand makes it unfeasible from an economic perspective compared to an alternative such as sustainable biomass or carbon capture and storage. Hence, Lechtenböhmer et al. conclude that the electrification of industry should be combined with increased efficiency, biofuels, and CCS. In a related study estimating the potential for electrification of industrial processes in Denmark, Bühler et al. [23] find that the majority of the Danish industry demand can be electrified, reducing the final energy demand by one-third. This is largely a result of increased heat pump (HP) integration. Not unlike the conclusion in Lechtenböhmer et al. Bühler et al. find that the economically feasible potential is considerably lower than the technical potential. Sorknæs et al. investigate the effects of direct electrification and indirect electrification through hydrogen fuel-shifting process for industry in a 100% renewable energy system, finding that from an energy system perspective direct electrification should be preferred where possible due to a higher energy system efficiency and thereby lower system cost [24].

The industry sector presents a significant unrealised potential for excess heat utilisation, particularly in combination with DH, as evident from studies on the excess heat potential in industry in Denmark [25] and Sweden [26]. Moreover, the use of excess heat significantly influences the need for electricity grid infrastructures [27]. However, as established in Brueckner et al. [28], a critical lack of industry energy data across different sectors is a huge obstacle to accurate quantification of excess heat potential, as data is sparingly available for many countries, and instead, authors need to rely on data from other countries when conducting studies.

Hence, from this brief overview of existing research, it is apparent that several studies on isolated sectors or individual decarbonisation measures exist, but there are limited studies presenting methodologies capable of encompassing the entire industry sector in detail. Studies on future renewable energy scenarios generally include the industry sector in an aggregated manner separated only by fuel types [29], as opposed to disaggregation by sub-sectors, products, and processes, and as such do not attend to the complexity and heterogeneity of the industry sector. Chang et al. conducted a review of energy system modelling tools, finding that industry is included to a varying degree and often overlooked entirely [30].

This paper aims to fill the gap by presenting a tool for bottom-up top-down modelling of decarbonisation scenarios for the industry sector in the context of renewable energy systems. A freeware tool including data is introduced whichand is based on a set of seven guiding principles for strategically implementing the Energy Efficiency First Principle into a decarbonised industry that is part of a future smart energy system. IndustryPLAN, a novel tool for analysing industry, is presented. This tool can assist in dissecting industry into its pertaining sub-sectors, production processes, and energy mitigation measures. In this paper, the tool is applied to the EU27 countries and the United Kingdom as a case to illustrate the implications of the Energy Efficiency First principle and the capability of the IndustryPLAN tool. The tool enables the creation of a large variety of scenarios implementing new technologies, changes in the connection with GDP, material efficiency, and considering temperature levels, and other industrial characteristics to enable a better fit with the overall energy system with a larger and larger penetration of renewable energy. The focus of the tool and the guidelines are to understand climate mitigation measures. However, both can also be used for analysing the competitiveness and resilience of industrial energy and technology investments in light of geopolitical issues such as the current energy price crisis or global supply chain challenges.

2. Methodology and guiding principles

In this section, we present the guiding principles for implementing the EE first principle in an industry sector fit for being part of a smart energy system. These will be critical in the transition of the industry sector, as several challenges and unanswered questions to the decarbonisation of industry persist. IndustryPLAN assists in answering the following needs for industry.

- A much deeper understanding of the industry sectors and their concrete temperature levels, concrete production processes and energy conversions.
- A systematic understanding of how to translate country-level energy consumption in industry, based on statistics, to tangible service demands divided by sectors.
- Enabling an understanding of the effect of the development in GDP on industry over time towards 2050, i.e., considering also potential accelerated globalisation with lower production levels or an automation tendency with increased production levels and energy consumption.
- Alignment with concrete options for using best available technologies (BAT) and using potential future technologies that are not necessarily currently commercially available now but are technically possible. With increasing implementation, the cost of such technologies would likely decrease while efficiencies would be improved.
- Alignment of possible technological changes within industry needs to assist with staying within the available resource levels within the whole renewable energy system and with types of energy carriers, i.e., renewable energy-based electricity, heat or gas from wind power, PV as well as geothermal and biogas etc.
- Specifically, a major focus should be on giving options for using other sources than biomass as bioenergy is a critical and limited resource.
- Enable that industry contributes to society with regards to waste heat for heating buildings using DH directly if temperature levels are high enough, or in combination with large-scale HPs for low-temperature waste heat.
- Enable an understanding of how energy use for industry can contribute and be part of Smart Energy Systems with highly integrated sectors through electrification, hydrogen, synthetic fuels and high amounts of fluctuating renewable energy sources. In addition, understanding how fossil and biomass-based materials for industrial products can be based on synthetic materials based on hydrogen, hydrocarbons and other electrofuels.

2.1. Seven guiding principles for energy efficiency in industry as part of smart energy systems

The guiding principles are defined out of the wish to transform the industry sector into a part of a future renewable energy system in which the energy consumption and the costs of the total energy system are minimized. This should be seen from a societal perspective which means that the end goal is not strictly optimizing the industry sector as an isolated sector, but instead, a system solution that is feasible considering the technical and economic feasibility of the entire energy system. In the overall system, biomass is a scarce resource and specifically biogas, wood waste, and straw are limited resources while also having different properties [31]. Biogas e.g., can be used for more processes than solid biomass and solid biomass can be used for more processes than electric boilers, HPs and low-temperature heat sources, also outside industry. Bioenergy is needed in other sectors such as the electricity and transport sectors which are otherwise hard to balance and completely decarbonise [32]. Resources need to be used where the greatest benefits can be obtained and wind power, photovoltaic, geothermal solar thermal etc. Are more abundant than bioenergy. Hence, the guiding principles for implementing the EE first principle in industry should be considered and applied in the context of designing renewable energy systems as part of national, international, or global strategies. The first version of these principles was presented in IDAs Energy Vision 2050 in 2015 [33].

Priority is given to savings, then to smart energy coordination with DH and cooling as well as electricity via HPs [34], and finally, to the replacement of fossil fuels with electricity, solid biomass and lastly biogas, hydrogen-upgraded biogas, hydrogen and PtX fuels (electrofuels). In general, in each guiding principle, at focus should be on BAT and innovative technologies. The seven guiding principles is illustrated in Fig. 1 and can be implemented as steps towards an EE-first industry compatible with renewable energy systems.

1. Energy savings and end-use EE re-thinking the production process:
   a. Identify means to reduce steps in the production process to reduce fuel consumption e.g., by making small adjustments in the end product.
   b. Identify symbioses, recycling, and reuse between processes focusing on energy and materials.
   c. Installing more energy-efficient units in the existing production process.
   d. Better control systems to reduce energy losses.
   e. Insulation of commercial and industrial buildings.
2. Share your waste heat sources internally and externally (industrial symbioses):
   a. Identify high-temperature waste heat (>100 °C), steam, pressurised heat or similar that could be used in other high-temperature processes internally or shared with other neighbouring industries.
   b. If high-temperature waste heat cannot be shared with other companies use it for building heating and cooling needs within the industry, with neighbouring companies and with the public DH or cooling grids.
   c. Identify low-temperature waste (<100 °C) heat and use this for internal heating and cooling needs, share it with neighbouring companies or with the public DH and cooling grid.
3. Use HPs for as high-temperature levels as technically possible and use DH and district cooling:
   a. If there is a need for low-temperature heating (<100 °C) and cooling that cannot be covered with waste heat from within the company, connect to the public DH grid, district cooling grid, or identify surrounding companies with waste heating or cooling available to share.
   b. Identify means to use HPs as much as possible for the processes within industry to the highest temperature level possible (normally <150 °C). Consider using higher-temperature heat sources than ambient air from within the industry, geothermal sources, seawater, groundwater, or a DH grid to increase the COP of the HPs.
   c. Use HPs for low-temperature processes, heating of buildings, hot water and cooling not covered by the above. If there is no connection to a DH or cooling grid, consider combining HPs for

Fig. 1. Illustration of the seven guiding principles for implementing the energy efficiency first principle in an industrial sector as part of renewable Smart Energy Systems.

low-temperature processes with small thermal storages to limit the use of bioenergy, direct resistance electric heating and natural gas, coal or oil.

4. Replace fossil fuels with non-fuel-based energy sources:
   a. For processes not able to have fossil fuels replaced by HPs, use electric boilers instead. This is typically higher temperature needs (>150 °C).
   b. Explore innovative technologies such as on-site concentrated solar with or without high-temperature thermal energy storage for high-temperature processes (>150 °C).
5. Replacing fossil fuels with solid biomass (wood waste, straw etc.):
   a. Use of biomass should be limited to those processes not possible to electrify with HPs or electric boilers. Use solid biomass only when needed for high-temperature processes.
6. Replace remaining fossil fuels with green gases (e.g., biogas, methanated biogas, hydrogen):
   a. Use biogas or upgraded biogas where electrification and dry biomass is not possible to use due to the need for high temperature. If biogas is not present or possible use gasified biomass.
   b. Use of green hydrogen, e-methane (methanated biogas) or other electrofuels produced with renewable energy in electrolyses in high-temperature industrial demands e.g., for iron and steel.
7. Additional measures (not included in IndustryPLAN):
   a. Onsite renewable energy production (e.g., building-level photovoltaics on large roofs). Use large roof areas or parking areas for deployment of large-scale photovoltaics if feasible.
   b. As a consequence of the electrification steps as well as the energy storages suggested, industries can explore the option of demand response to either exploit low energy prices and/or to ensure the use of renewable energy based electricity.
   c. Use carbon capture utilisation and storage (CCUS) in hard-to-abate sub-sectors

In guiding principle number 7 we go beyond the scope of the EE first principle and outside the scope of the IndustryPLAN tool. For completeness of measures on-site in the guiding principles, we include this focus. Many industries have a large electricity consumption, have close neighbours with high electricity consumption and have large roofs or parking lots possible to mount photovoltaics. On a societal level, this has the advantage that greenfield utility-scale photovoltaics can be avoided, and that grid expansion can be minimized with renewable energy production closer to the demand [35].

For industry as a part of renewable energy based smart energy systems a focus on EE is more important than creating flexibility within the industrial site itself. However, in the guiding principles thermal energy storage is included as a potential future option due to the advantages obtained from combining storage and large-scale HPs or concentrated solar. Even a small capacity of low- or high-temperature thermal storage may help eliminate other fuels such as bioenergy, natural gas, coal, oil, or direct electricity.

3. IndustryPLAN tool design and functioning

IndustryPLAN is a tool for analysing the industrial energy demands of European countries. The tool is developed as a Microsoft Excel spreadsheet using a combination of Excel functions and VBA coding, making the tool accessible to a wide audience. The tool provides a bottom-up top-down approach in which first the "black box" of industry is opened up with country-based data and technology data from the bottom-up assessment of each industrial sector. In a top-down approach, measures are implemented on the sub-sectors, aggregated, and connected to GDP development and saturation rates of new technologies. The IndustryPLAN tool is established based on the following overarching ambitions.

1. To provide a platform for implementing the guiding principles for EE in industry.
2. Enabling the establishment of tangible future scenarios for the industry sector as a part of smart energy systems.

This paper includes the IndustryPLAN tool as supplementary material in Appendix A including all input data per industrial sector and divided into EU27 + UK and assumptions on fuel costs, implementation rates, energy savings potential, and investment costs. The latest version is available online [36]. While this paper introduces the tool design and functioning, further information on the included EE measures can be found in a publication by Kermeli et al. [37], and different 100% renewable energy industry scenarios are explored with the IndustryPLAN tool in a publication by Johannsen et al. [38]. Further information is available in background reports [39,40].

Fig. 2 provides an overview of the main data inputs to IndustryPLAN and the main outputs.

As can be seen in Fig. 2, IndustryPLAN provides many different results aimed at evaluating and quantifying future industrial energy demands. Combined with the included scenario design functionality, these outputs can aid in the investigation of a wide array of research questions, such as analyses on the importance of energy savings, and the impact of extensive electrification or conversion of fossil fuel-based processes to biomass and hydrogen-based processes. IndustryPLAN enables a flexible perception of industry if combined with heat storage, hydrogen storage etc. While such analyses and results specifically for the industry sector are interesting on their own, an important capacity of IndustryPLAN is that it can provide inputs for holistic energy system models encompassing complete national energy systems, including the heat, electricity, industry, and transport sectors. Thus, the disaggregated and detailed industry assessment from IndustryPLAN can provide a more thorough representation of the industry sector in modelling of integrated energy systems.

3.1. Outset for industrial sector analyses and energy efficiency measures

Before identifying the EE potentials and constructing the EE and decarbonisation scenarios a scenario was developed that takes into account the currently expected industrial developments. The reference scenario by the European Commission (2016) [41], makes final energy demand projections per industrial sub-sector and EU country up to 2050 while capturing current policies and market trends. However, because no insight into the EE uptake is given - crucial information that dictates the current and future untapped EE potential - a frozen efficiency scenario was constructed. The frozen scenario was developed so that it captures the same structural changes as the reference scenario by the European Commission but without EE improvements.

The final energy demand in the base year (2015) for all industrial sub-sectors was taken from PRIMES [41]. It was then divided per main industrial product based on the activity level in 2015 (from available statistics) and the average energy intensity (in GJ/tonne) per industrial product (from statistics and literature). The future energy demand in the frozen efficiency scenario was then determined by using the PRIMES production developments and by assuming that energy intensity remains at the 2015 level. The energy demand per industrial sub-sector and country was broken down per energy carrier (coal products, oil products, peat products, natural gas, biofuels and waste, heat, geothermal, electricity, and hydrogen) based on the IEA database [42].

In the next step, the EE measures/technologies that could offer significant energy savings were identified and information was collected on the base year diffusion rates, energy savings potentials (in GJ/tonne), investment costs (in 2015€/tonne) and change in operation and maintenance costs (in 2015€/tonne). Future diffusion rates were assigned per technology for 2030 and 2050 based on available literature [37], where for most technologies the diffusion would reach 100% by 2050. All similar information was also collected for the innovative, electrification, and hydrogen technologies. The savings potentials in these cases would consider that the technologies they replace have already improved their EE.

The industrial products assessed were ethylene, methanol, ammonia, crude steel (via the blast furnace and electric arc furnace), rolled steel, coke, steel castings, primary aluminium, secondary aluminium, aluminium casting, cement, flat glass, container glass, paper and pulp. The energy demand not assigned to these products was either included in the remaining energy demand of the industrial sub-sector (i.e., the energy use in sinter plants was assigned into the "Rest iron and steel industry") or in the Others industrial sub-sector (e.g., the energy demand for engineering, food, drinks and textiles). For more details see Kermeli and Crijns-Graus [40].

3.2. Tool outputs

After designing a scenario and exporting results for all countries several different outputs can be extracted from the resulting data set. This section will introduce some of the main outputs and results established by the tool. A more practical illustration of the results is then included in Section 4, where the results for the selected scenarios are presented. See Appendix B for the complete dataset with scenario outputs.

3.2.1. Final energy demands

Energy demands are available for all countries, sub-sectors, and fuel types. Energy demand in this context also includes electricity and

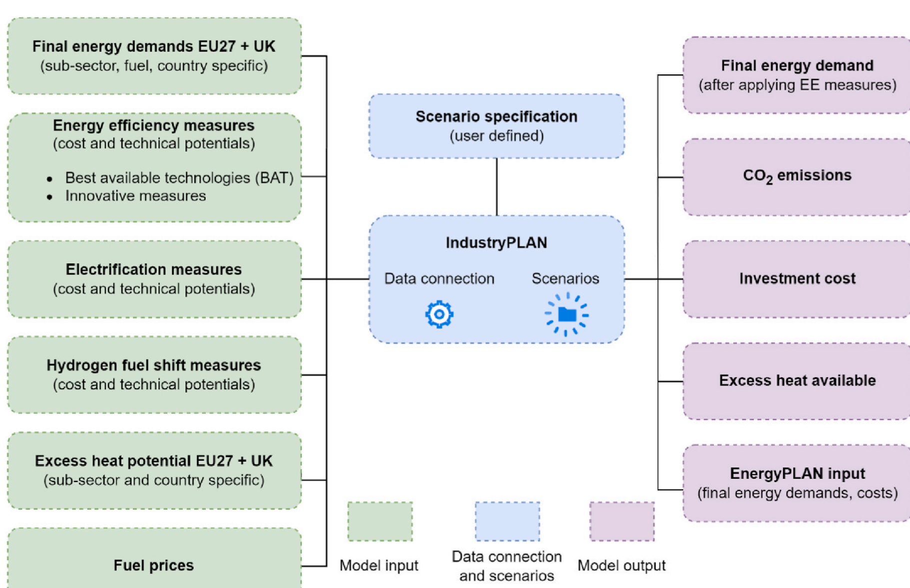

Fig. 2. Overview of IndustryPLAN model.

hydrogen demand, and any potential increase in the demand that may have occurred as a result of increased electrification or a shift to hydrogen-based processes. Energy demands are included for the base year 2015, the frozen efficiency scenario in 2030 and 2050, and the user-specified mitigation scenario in 2030 and 2050. The base year and frozen efficiency scenarios are included so that comparisons on both absolute and relative differences can be made. From the energy demand results, renewable energy shares can be calculated on both a country and sub-sector level. The base year and target years can be updated depending on data availability and the purpose of the study. The energy demands do not include energy for non-energy use purposes.

3.2.2. CO_2 emissions

Based on the energy demands per fuel type and fuel emission factors, CO_2 emissions are calculated for every fuel type and sub-sector. Hence, CO_2 emissions can be aggregated either by country, sub-sector, or fuel type as desired. Again, comparisons can be made to the base year and frozen efficiency scenarios.

3.2.3. Investment costs

Investment costs are calculated for the mitigation measures implemented and disaggregated per sub-sector. The investment costs for the mitigation measures are separated from the investment cost needed for excess heat utilisation in DH.

3.2.4. Fuel costs

Annual fuel costs are calculated for each scenario and sub-sector. Fuel costs are separated by fuel type and include both the cost of fuel and, where applicable, fuel handling costs, and can be included at three different price levels. Fuel costs can be adjusted freely by the user as needed. The fuel prices assumed for this study can be seen in Table 1.

3.2.5. Excess heat

Results for excess heat production for DH include the actual excess heat potential, the electricity demand for HPs if they are installed for boosting the temperature, and the investment costs for those HPs and the needed heat exchangers. Here it should be noted that the investment costs do not include any potential expenses for expanding the DH grid.

Further details on tool outputs and input data are available in Appendix A and Appendix B.

3.3. EnergyPLAN integration

An important functionality of the IndustryPLAN tool is that the output can serve as an input for EnergyPLAN [18] where further integrated energy system modelling can be conducted. This allows for analyses of how the industrial energy sector interacts with the surrounding energy system, and not only looking at the industrial sector in a vacuum.

Table 1
Assumed fuel costs.

Fuel type	Fuel price [EUR/GJ]	Fuel price [EUR/GJ]	Source
	2030	2050	
Coal and coal products	2.73	2.69	IEA WEO 2020 (stated policies) [43]
Oil products	12.30	13.92	IEA WEO 2020 (stated policies) [43]
Natural gas	7.34	8.92	IEA WEO 2020 (stated policies) [43]
Biomass	16.08	16.48	Danish Energy Agency fuel price projections [44]
Heat	18.10	18.10	European District heating price series [45]
Electricity	12.70	12.70	Danish Energy Agency fuel price projections [44]
Hydrogen	24.80	24.80	IEA Future of hydrogen [46]

This section will briefly introduce how the IndustryPLAN outputs may be integrated into EnergyPLAN.

EnergyPLAN is a tool for simulating hourly energy balances for all energy sectors, including heating, electricity, gas, transport, industry, and water desalination. While the industry sector is included in the current EnergyPLAN tool, it is currently represented only through a simple and aggregated methodology where the user can define total fuel demands by fuel type. This does not allow for any further details and differences across industry sub-sectors, temperature levels, or energy mitigation measures. IndustryPLAN makes it possible to generate more detailed industry scenarios, before returning to the holistic energy system modelling in EnergyPLAN and thus the two tools complement each other.

4. Industry scenario results

In this section, future industry scenarios for 2030 and 2050 are presented for a combined EU27 + UK and are compared to a 2015 baseline and a frozen efficiency scenario. The scenarios are established through the application of the guiding principles for industry transitions as presented in Section 2 and modelled with the IndustryPLAN tool described in Section 3. The purpose is to apply and test the established guiding principles for EE and to provide a practical overview of the main capabilities of the IndustryPLAN model.

In the modelled scenarios industry is disaggregated into seven sub-sectors and 23 individual products. This disaggregation is shown in Table 2. The production volumes shown assume that no additional EE improvements are implemented and thus serve as the basis for the Frozen Efficiency scenario. Non-energy use demands (e.g., feedstocks in the chemicals industry) are excluded from the resulting final energy

Table 2
Industry sub-sectors and production volume developments in IndustryPLAN for the Frozen Efficiency scenario [29].

Industrial sub-sector	Product	2015	2030	2050
		[kt]	[kt]	[kt]
Chemicals	Carbon black	998	1121	1166
Chemicals	Ethylene	16,810	18,091	18,306
Chemicals	Methanol	1,438	1,725	1,812
Chemicals	Ammonia	17,394	18,146	18,137
Chemicals	Soda ash	6,025	6,323	6,252
Foundries	Ferrous metals casting	10,185	10,912	11,091
Foundries	Non-ferrous metals casting	3,672	3,972	3,972
Iron and steel	BF/BOF[a] steel	100,864	106,921	110,129
Iron and steel	Pig iron	93,596	104,860	106,780
Iron and steel	Rolled steel	150,924	143,279	119,453
Iron and steel	EAF[b] steel	65,429	69,355	71,436
Iron and steel	Coke oven coke	32,586	34,432	34,724
Non-ferrous metals	Aluminium primary	2,242	2,422	2,398
Non-ferrous metals	Aluminium secondary	3,300	3,488	3,438
Non-metallic minerals	Cement	168,170	200,917	204,500
Non-metallic minerals	Flat glass	11,617	12,846	13,387
Non-metallic minerals	Container glass	15,317	15,844	14,149
Paper and pulp	Tissue paper	7,175	7,762	7,889
Paper and pulp	Graphic paper	34,566	37,041	37,609
Paper and pulp	Board and packag. Paper	46,114	49,512	50,606
Paper and pulp	Chemical pulp	25,582	27,000	27,693
Paper and pulp	Mechanical pulp	8,236	8,712	8,939
Paper and pulp	Recovered fibre pulp	21,294	22,489	23,247

[a] Blast furnace/Basic oxygen furnace.
[b] Electric arc furnace.

demands.

Taking the production volumes from Table 2 as a starting point, six mitigation scenarios are investigated. An overview of these can be seen in Table 3.

While IndustryPLAN allows for developing other scenarios and combinations of energy mitigation measures than those included in Table 3, results are presented for a limited selection as the primary purpose is to demonstrate the applicability of the guiding principles and the capability of the IndustryPLAN tool. The maximum EE and 100% renewable energy (Max EE+100% RE) scenario constitutes a scenario that can be based on 100% renewable energy, provided that the electricity supply is based on renewable energy sources such as wind power, solar or geothermal sources. This scenario combines electrification measures and hydrogen fuel shifting measures, where hydrogen is exclusively for high-temperature processes.

Recycling as included in the scenarios in Table 3 represents the potential for material recycling improvements in main industries, where the high recycling scenario corresponds to e.g., an increased share of steel production from scrap steel from 39% in 2015 to 67% in 2050 [47] or a reduction of the clinker to cement ratio from 76% in 2015 to 66% in 2050 [48]. A compete overview of the included EE improvements can be seen in Kermeli et al. [37].

The results and scenario outputs presented in this section will focus on the aggregated results for the EU 27 + UK countries, however, this is an aggregate of preceding individual country modelling in IndustryPLAN.

4.1. Energy savings and energy efficiency (guiding principle 1)

Following the guiding principles firstly energy-saving and EE improvements should be considered. This includes recycling materials or implementing more efficient industrial processes.

The results shown in Fig. 3 indicate that both the implementation of BATs and high recycling rates can lead to significant energy savings, as evident from the BAT (no recycling) and BAT (high recycling) scenarios. Further adding innovative measures on top of the BATs lead to even more savings, especially for 2050 when these specific measures are expected to be more readily available. The electrification and hydrogen scenarios result in a shift of fuel demands to electricity and hydrogen respectively.

The estimated energy savings potential for 2030 is shown in Table 4 and for 2050 in Table 5.

The total energy savings (across all sub-sectors) per scenario is shown in Table 6. From this, it is evident that a significant portion of the energy savings potential lies beyond 2030, as implementation rates and general technological readiness increase for energy mitigation measures and technologies.

Table 3
Industry energy mitigation scenarios investigated.

Scenario	Mitigation measures	Recycling	Excess heat
BAT (no recycling)	BAT	No extra recycling	All excess heat
BAT (high recycling)	BAT	High recycling	All excess heat
BAT + innov. (high recycling)	BAT + innovative	High recycling	All excess heat
BAT + elec. (high recycling)	BAT + electrification	High recycling	All excess heat
BAT + H2 (high recycling)	BAT + hydrogen	High recycling	All excess heat
Max EE+100% RE	All	High recycling	All excess heat

4.2. Excess heat and district heating (guiding principles 2 and 3)

Following the guiding principles, after implementing EE improvements, integration of excess heat into the surrounding energy system should be considered to provide system-wide EE improvements. The excess heat potential is estimated at three temperature levels, 25 °C, 55 °C and 95 °C. These temperature levels are selected to correlate to the temperatures required in 3rd and 4th generation DH systems [49]. Excess heat at 95 °C could be used directly in 3rd generation DH, while excess heat at 55 °C could be used directly in 4th generation DH. Excess heat at 25 °C could be used as a low-temperature heat source for HPs and boosted to 55 °C to be used in 4th generation DH.

The assessment of excess heat potential is correlated to the general GDP development and thereby the projected development of industrial production volumes and material demands, where an increase in production volume results in an increased excess heat potential, and vice versa. The excess heat potential is also correlated to the level of recycling implemented, where a high recycling rate (e.g., increased recycling of scrap steel) results in a lower required production volume, and thereby a lower excess heat potential. Finally, the assessment of excess heat is connected to the implementation of BAT measures, where implementation of more efficient processes with increased internal use of excess heat reduces the excess heat potential available for DH. With these considerations, the excess heat potential in Fig. 4 is relatively conservative, as both a complete implementation of BAT measures is assumed and a complete change in recycling practices.

The estimated excess heat potential for the BAT scenario with and without additional recycling can be seen in Fig. 4.

The largest excess heat potentials are found in the Others sub-sector, which mainly includes food and beverage production, followed by the non-metallic minerals sub-sector, consisting of high-temperature processes such as cement production.

A limitation of the tool is that the impact of innovative technologies, electrification, and hydrogen fuel shifting measures are not included in the excess heat potential. This is a limitation of the tool due to data availability. Naturally, these changes to the industry sector would have some impact on the excess heat potential. However, even in a highly electrified scenario, some excess heat would be available from biomass and hydrogen-based processes, and an additional excess heat potential would be available from the production of hydrogen from electrolysis. Determining the excess heat potential from electricity-based industrial processes is difficult, but high-temperature processes (e.g., from electric arc furnaces) would likely still have some excess heat potential even if based on electricity. Excess heat potentials from industry for DH were also assessed in a comprehensive study by Manz et al. however, this study also does not determine the impact of widespread electrification on the excess heat potential [50].

In Table 7 the required HP capacity in DH can be seen if the temperature would need to be increased to 75 °C. It is assumed that HPs are implemented to boost the excess heat supplied at 25 °C and 55 °C, while the excess heat supplied at 95 °C does not require boosting, and hence no HP capacity is needed.

A lower installed HP capacity is found for 2050 due to an expected lower potential from some of the energy-intensive processes, particularly in the iron and steel and non-metallic minerals sub-sectors. This is exacerbated in the high recycling scenario, as high recycling rates lead to further reductions of the excess heat potential.

4.3. Replace fossil fuels (guiding principles 4–6)

In the guiding principles steps 4–6 it is detailed how fuel shift measures should be implemented after EE improvements and DH integration opportunities have been exhausted. This entails replacing fossil fuels with electricity, biomass, or green gasses. To illustrate how the fuel distribution per scenario changes following this, a detailed distribution of fuel demands per scenario is shown in Fig. 5. For comparison, the EU

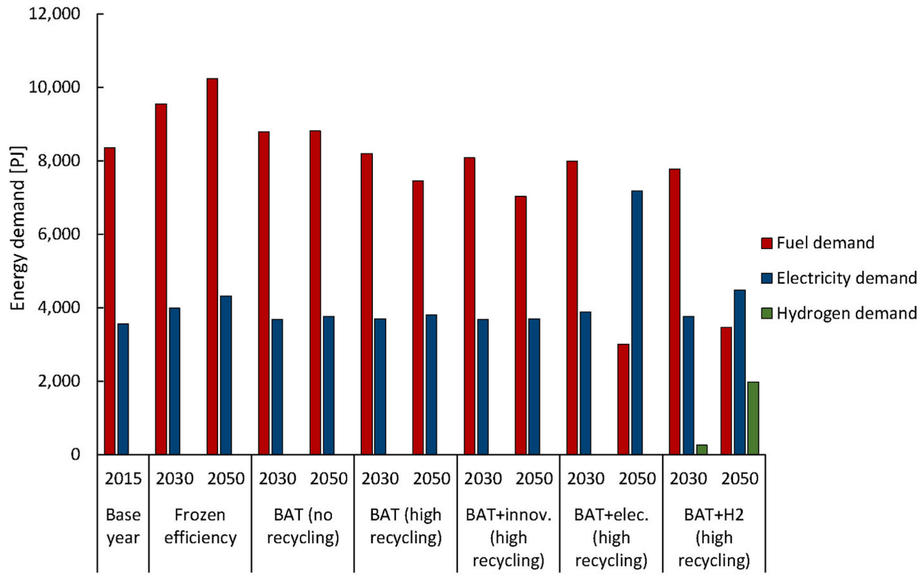

Fig. 3. Energy demand by scenario for EU27 + UK.

Table 4
Energy savings potential per sub-sector for 2030 compared to frozen efficiency scenario.

2030 Scenario	Chemicals	Foundries	Iron and steel	Non-ferrous metals	Non-metallic minerals	Paper and pulp	Others
BAT (no recycling)	5.8%	6.8%	10.5%	10.4%	10.4%	2.4%	8.0%
BAT (high recycling)	5.8%	6.8%	21.7%	14.9%	17.0%	2.4%	11.9%
BAT + innov. (high recycling)	5.8%	6.8%	24.9%	15.3%	18.6%	3.9%	11.9%
BAT + elec. (high recycling)	6.4%	14.1%	21.9%	15.4%	17.9%	7.1%	9.8%
BAT + H2 (high recycling)	6.4%	6.8%	21.9%	15.3%	17.7%	4.0%	12.9%

Table 5
Energy savings potential per sub-sector for 2050 compared to frozen efficiency scenario.

2050 Scenario	Chemicals	Foundries	Iron and steel	Non-ferrous metals	Non-metallic minerals	Paper and pulp	Others
BAT (no recycling)	8.6%	15.3%	16.8%	22.0%	20.8%	4.6%	13.9%
BAT (high recycling)	8.6%	15.3%	41.9%	33.6%	33.2%	4.6%	22.1%
BAT + innov. (high recycling)	8.6%	15.3%	48.7%	39.5%	43.0%	14.5%	22.1%
BAT + elec. (high recycling)	13.3%	43.8%	31.1%	35.4%	38.2%	46.7%	28.4%
BAT + H2 (high recycling)	11.1%	15.3%	28.9%	34.8%	36.2%	18.4%	42.9%

Table 6
Total energy savings potential compared to frozen efficiency scenario.

Scenario	2030	2050
BAT (no recycling)	7.79%	13.59%
BAT (high recycling)	12.15%	22.74%
BAT + innov. (high recycling)	13.08%	26.28%
BAT + elec. (high recycling)	12.23%	29.98%
BAT + H2 (high recycling)	12.91%	31.73%

1.5 TECH scenario is included. For the 1.5 TECH scenario, the final energy demand is estimated based on the EU "Clean Planet for All" report [51], in which energy savings of 10% and 22% relative to 2015 are stated for the 1.5 TECH scenario in 2030 and 2050 respectively (see Fig. 6).

The most drastic changes in terms of fuel distribution occur for the BAT + elec. (high recycling) and BAT + H2 (high recycling) scenarios, where the electricity and hydrogen demand increases. It should, however, be noted, particularly for the hydrogen scenario, that the electricity demand does not account for the electricity required for hydrogen production e.g., through electrolysis. The results shown in Fig. 5 should be considered to represent the demand side of the industrial sector, and hence the electricity demand located outside of the industrial sector for this hydrogen production needs to be accounted for elsewhere in

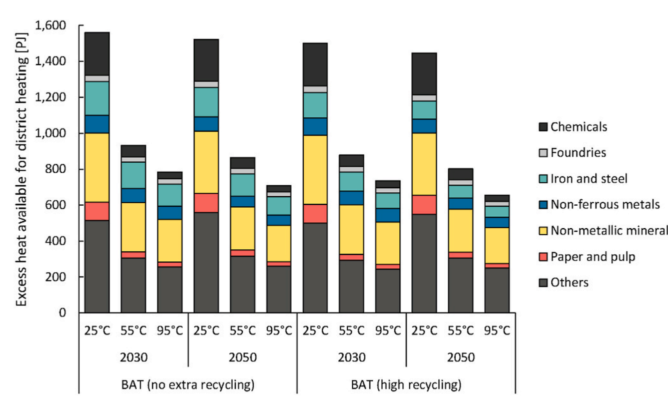

Fig. 4. Excess heat potential available for DH per sub-sector and temperature level for EU27 + UK.

Table 7
HP capacity needed for the utilisation of excess heat in DH.

Scenario	Temperature level	2030 [GW_t]	2050 [GW_t]
BAT (no extra recycling)	25 °C	87.10	84.94
	55 °C	46.91	43.49
BAT (high recycling)	25 °C	83.80	80.75
	55 °C	44.20	40.34

integrated energy system analysis. Similarly, the electricity demand does not include the electricity demand for the HP operation in DH related to the use of excess heat in DH.

Compared to the EU 1.5 TECH scenario, where the distribution of fuel types is not specified, energy demands in the scenarios outlined in this study are generally higher. It is also not specified in detail how the significant energy savings included in the EU 1.5 TECH scenario are to be realised. It is however apparent that the EU 1.5 TECH scenarios are relatively optimistic regarding the future potential for energy savings. The EU 1.5 TECH scenario thereby represents the typical "black box"-approach to industry sector modelling, in which scenarios are not immediately connected to concrete mitigation measures.

The scenarios BAT (no recycling), BAT (high recycling), and BAT + innov. (high recycling) do not include fuel-shifting measures or technologies but only fuel or electricity-saving measures, and hence the fuel distribution is not highly affected by the changes implemented.

The BAT + elec (high recycling) and BAT + H2 (high recycling) scenarios include extensive electrification and a shift to hydrogen-based processes, resulting in a higher renewable energy share and reduced CO_2 emissions (Table 8), assuming that the electricity and hydrogen used are from renewable sources. This is perhaps an ambitious assumption, and especially for 2030 may be difficult to reach. However, limited electrification and hydrogen shift are expected to occur before 2030 and thus this does not influence the 2030 results much.

While the CO_2 emissions for the BAT + elec. (high recycling) and BAT + H2 (high recycling) scenarios appear low, again it should be emphasised that this is based on the assumption of 100% renewable electricity. If hydrogen production is instead based on electricity from coal or natural gas-fired power plants, the CO_2 emissions will be higher (i.e., the LCA-based differences between green, black and blue

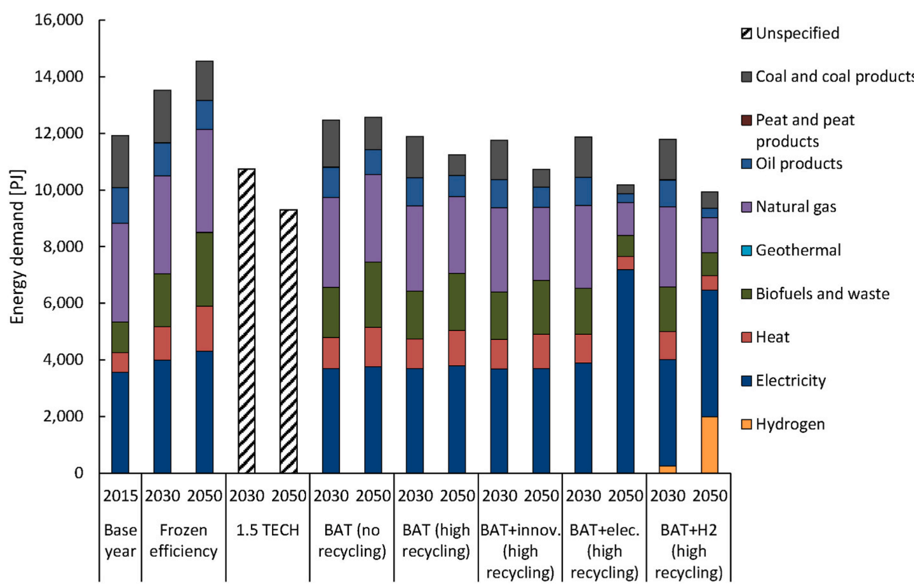

Fig. 5. Scenarios for final energy demand by energy type for EU27 + UK.

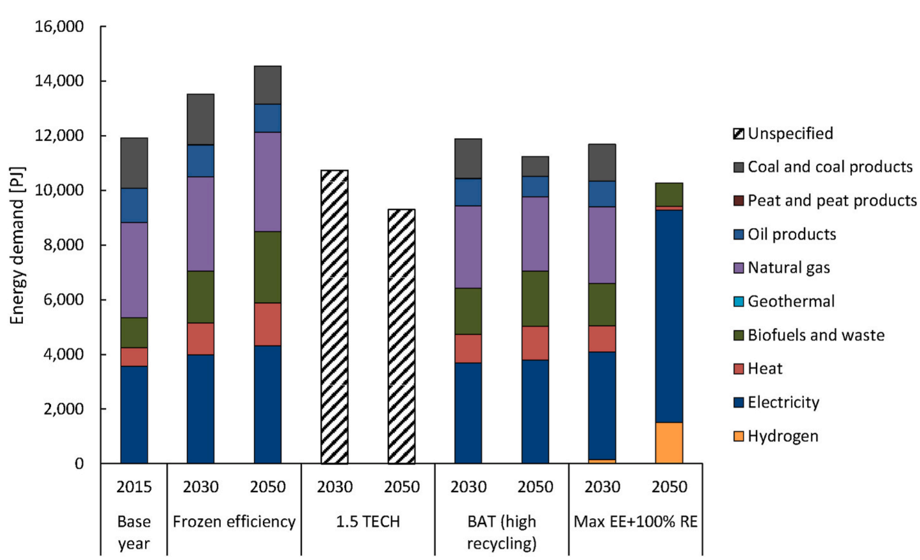

Fig. 6. Selected final energy demand scenarios by energy type for EU27 + UK incl. A 100% renewable energy scenario.

Table 8
Total CO_2 emission savings compared to frozen efficiency scenario.

Scenario	2030	2050
BAT (no recycling)	8.84%	15.51%
BAT (high recycling)	16.70%	32.69%
BAT + innov. (high recycling)	18.24%	37.49%
BAT + elec. (high recycling)	18.30%	71.19%
BAT + H2 (high recycling)	20.20%	63.85%

hydrogen).

4.4. *100% renewable energy in industry*

A 100% renewable energy scenario is possible in 2050. Here one possible option for achieving this is illustrated through the Max EE+100% RE scenario included in 6. In the Max EE+100% RE scenario, 100% renewable energy is achieved through high amounts of energy savings, significant electrification, and some use of hydrogen and biomass for hard-to-abate sectors. The guiding principles and IndustryPLAN do not as such include limitations on the use of biomass. However, the method emphasises minimising the use of bioenergy. A sustainable level of biomass consumption in each of the analysed scenarios is dependent upon the geographical area and on the use of bioenergy in other sectors e.g., transport and combined heat and power [4].

Final energy demands per sub-sector and fuel type can be seen for the Frozen Efficiency and Max EE+100% RE scenarios in Fig. 7.

Annual costs for the industry sector can be seen in Fig. 8. The results do not include costs for CO_2 emissions, which would bring the results for the Max EE+100% RE scenario more in line with the other scenarios depending on whether the externality costs or emission trading system (ETS) costs are included. Here the fuel costs are illustrated for one set of fuel prices, the tool however enables analysis of up to three price levels.

It is not possible to compare the results of the IndustryPLAN modelling to the costs of the modelling in the EU 1.5 TECH scenario as details of the model are not disclosed. It is nevertheless likely that the cost of the 1.5 TECH scenario is somewhere in between the cost estimated for the BAT and the Max. EE+100% RE scenarios, depending on the extent to which hydrogen is used. It is uncertain precisely the fuel mix and measures included in the 1.5 tech scenario.

With the combination of the guiding principles for the industrial energy transition and the IndustryPLAN tool, we now have the resources needed to adequately plan for the integration of the industrial sector in renewable energy systems thoroughly and consistently. The guiding principles provide a concrete, feasible and actionable pathway for the industrial energy transition, while the IndustryPLAN tool provides the concrete sector-based bottom-up EE measures necessary for opening the black box of industry scenarios.

5. Conclusions

The industry sector has so far largely remained a black box in energy system modelling due to a combination of complex challenges including a lack of energy and production data, lacking categorisation of current and future technologies and energy mitigation measures, and the general complexity and heterogeneity of the industry sub-sectors and processes.

In this study, we establish the EE first guiding principles, which are measures guiding and prioritising the renewable energy transition of the industry sector. The EE first principles can assist both policymakers and model developers in prioritising actions and measures for the industry sector in future holistic renewable energy scenarios. The purpose of the guiding principles is to ensure that the renewable energy transition occurs in the most efficient way considering a societal economic and technical perspective, in line with the principles of the Smart Energy Systems concept.

An IndustryPLAN tool has been prepared, applying the established EE first principles, and providing a platform for the design of industrial mitigation scenarios. The tool provides access to energy demands for the EU27 countries and the United Kingdom for seven industrial sub-sectors further disaggregated by fuel type. This demand data functions as the foundation of the tool and a baseline scenario and a frozen efficiency scenario. This is supplemented by an extensive catalogue of mitigation measures such as energy-saving measures, electrification measures, and hydrogen fuel shifting measures. The tool furthermore includes data on the potential for extraction of excess heat for external use in DH and supplying this excess heat at temperatures of 25 °C, 55 °C, and 95 °C, also disaggregated on a sub-sector level.

The tool enables the user to conduct country-specific as well as aggregated European analyses of climate mitigation measures such as the implementation of best available technologies, innovative measures and technologies, electrification, shift to hydrogen-based processes, and excess heat utilisation. Tool outputs are primarily: final energy demands

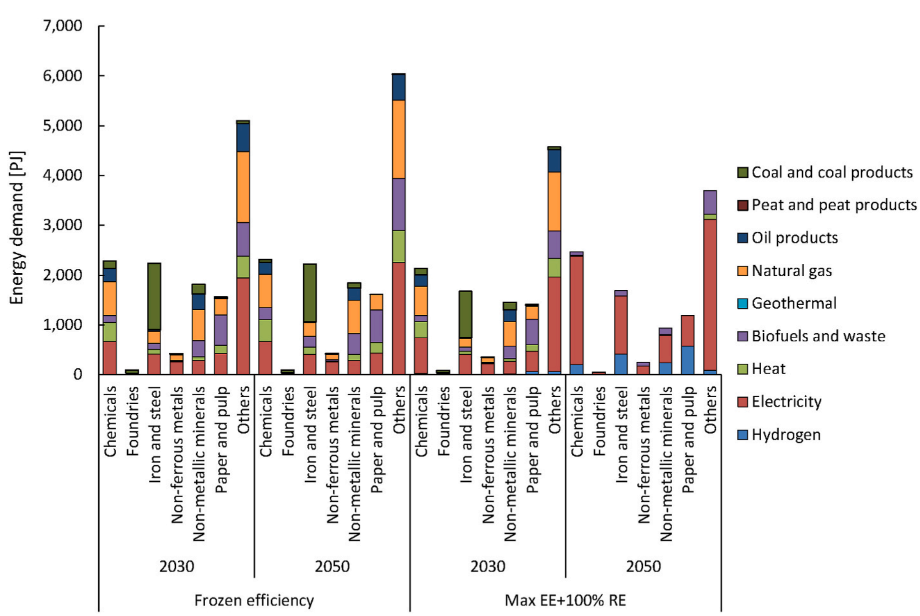

Fig. 7. Final energy demand per sub-sector and fuel type for Frozen Efficiency and Max EE+100% RE scenarios.

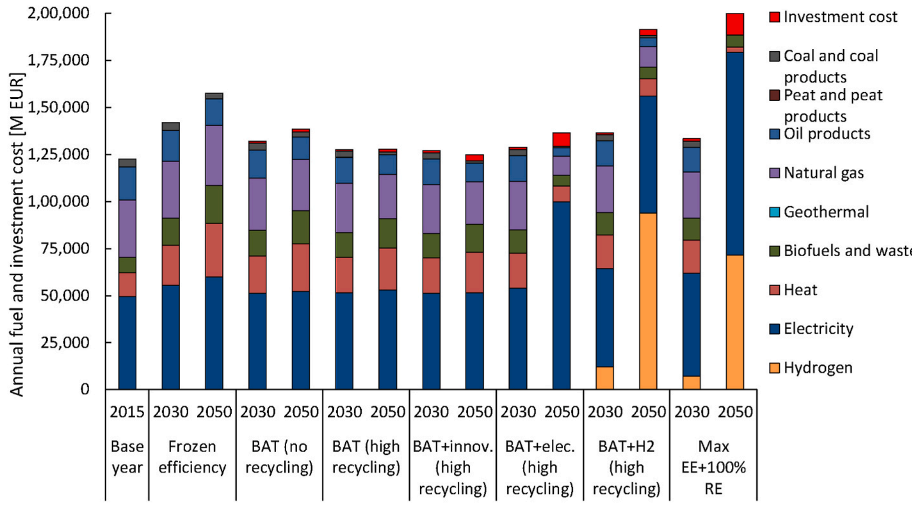

Fig. 8. Annual fuel cost and annualised investment for selected scenarios for EU27 + UK.

after implementation of the specified mitigation measures, related investment costs, and input for EnergyPLAN where further integrated energy system analyses can be done. The tool also enables analyses of the resilience towards fluctuating energy prices or technology costs due to geopolitical disputes or global supply chain challenges.

To illustrate the application of the guiding principles and the IndustryPLAN tool future industry scenarios for EU27 + UK were developed. These were compared to the EU 1.5 TECH scenario, illustrating the highly optimistic assumptions underlying the EU 1.5 TECH scenario and its assumed unspecified energy savings potential. The combination of the guiding principles methodology and the IndustryPLAN tool identifies at least 30% feasible final energy demand savings and the possible full decarbonisation of industry in a 100% renewable energy system, provided that the electricity supply is decarbonised.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This paper is part of the sEEnergies project which has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 846463 (www.seenergiesproject.eu).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.segy.2023.100111.

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